High-energy Cosmic Rays and Neutrinos from Semi-relativistic Hypernovae

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The origin of the ultrahigh-energy (UHE) cosmic rays (CRs) from the second knee ($\sim 6\times10^{17}$eV) above in the CR spectrum is still unknown. Recently, there has been growing evidence that a peculiar type of supernovae, called hypernovae, are associated with sub-energetic gamma-ray bursts (GRBs), such as SN1998bw/GRB980425 and SN2003lw/GRB031203. Such hypernovae appear to have high (up to mildly relativistic) velocity ejecta, which may be linked to the sub-energetic GRBs. Assuming a continuous distribution of the kinetic energy of the hypernova ejecta as a function of its velocity $E_k \propto (\Gamma\beta)^{-\alpha}$ with $\alpha \sim 2$, we find that 1) the external shock wave produced by the high velocity ejecta of a hypernova can accelerate protons up to energies as high as 10^{19} eV; 2) the cosmological hypernova rate is sufficient to account for the energy flux above the second knee; and 3) the steeper spectrum of CRs at these energies can arise in these sources. In addition, hypernovae would also give rise to a faint diffuse UHE neutrino flux, due to $p\gamma$ interactions of the UHE CRs with hypernova optical-UV photons.

PACS numbers: 98.70.Sa, 97.60.Bw 98.70.Rz,

There is a general consensus that galactic supernova remnants (SNRs) are responsible for the CRs at energies below the "knee" at $\sim 3\times10^{15}$ eV [1], most probably through the diffusive shock acceleration mechanism [2]. Galactic SNRs expanding into their former stellar wind have been suggested to be responsible for CRs above the knee [3]. Recent data from the KASCADE experiment suggest that heavy elements of nuclear charge Ze are accelerated by the galactic SNRs to the magnetic rigidity limit $\sim 3\times10^{15}Z$ eV [4]. Thus galactic SNRs may be able to produce CRs to at least $\sim 10^{17}$ eV (see e.g. [5, 6] for recent reviews), an energy slightly below the "second knee" in the CR spectrum at $\sim 6\times10^{17}$ eV (see e.g. [7]). On the other hand, the highest energy CRs above a few times 10^{19} eV are generally thought to be extra-galactic in origin, due to their isotropic distribution and a lack of galactic source candidates capable of producing them. At these energies, the possible sources include cosmological GRBs [8], active galactic nuclei [9] and powerful radio galaxies [10].

The origin of the intermediate energy range CRs, $10^{17}-10^{19}$ eV, however, remains more elusive. Some authors have suggested a common galactic origin for all CRs between the first knee and 10^{20} eV in young neutron stars or Magnetars [12], while others favor an extra-galactic origin of all CRs above 10^{18} eV [6, 9, 11]. Recent HiRes data shows that the transition from heavy nuclei to the proton composition may already occur at the second knee [13], suggesting that the UHE cosmic-rays with energy from 6×10^{17}eV above are all probably extra-galactic [6, 11]. In this paper we show that the energetics and spectrum of CRs from the second knee to 10^{19}eV may be due to extra-galactic hypernovae, similar to the hyper-energetic supernova SN1998bw.

SN1998bw was striking not only in its unusually large explosion energy, $E\simeq 3-5\times10^{52}$erg (so called "hypernovae" [14]), but also in that it was associated with a very sub-energetic GRB, GRB980425, with an isotropic equivalent gamma-ray energy $E_\gamma \simeq 10^{48}$ erg [15]. The possible transition from extreme SNe to GRBs was implied in the magneto-rotational mechanism of the SN explosions proposed in Ref.[16, 17]. Now the connection between GRB and SNe has been established through observations. The hypothesis for SN-associated GRBs such as GRB980425 that their weakness is an apparent effect due to seeing the explosion off-axis runs counter to observational tests based on long-time radio observations [18], so it is likely that this GRB is inherently dimmer than typical. The observations of the radio afterglow of this event showed that about 10^{50} erg of kinetic energy were released in the form of a mildly relativistic ejecta [19]. Due to the large supernova explosion energy and the much lower than typical GRB energy, attempts have been made to ascribe the GRB event to the shock from the mildly relativistic ejecta as it breaks out through the hypernova progenitor's outer envelope [20, 21]. A generally accepted conclusion, however, has not yet been reached. A recently detected strong thermal X-ray emission component in another sub-energetic burst (GRB060218), associated with SN2006aj, may also be associated with a semi-relativistic supernova shock breakout, in which the mildly relativistic supernova ejecta has an energy $\gtrsim 10^{49}$ erg [23]. The radio observations of this burst, as well as those of another hypernova burst, GRB031203/SN2003lw, also indicate that there is a significant energy in the mildly relativistic ejecta [24]. We will use the term semi-relativistic hypernovae to denote such supernovae exhibiting a mildly relativistic ejecta component, seen in association with GRBs. The recently discovered SN2006gy [25] also has a large explosion energy, but continued multi-wavelength monitoring has not yielded any evidence for an associated GRB, so this object may be in the class of normal hypernovae with large explosion energy, but without any significant mildly-relativistic ejecta [26].

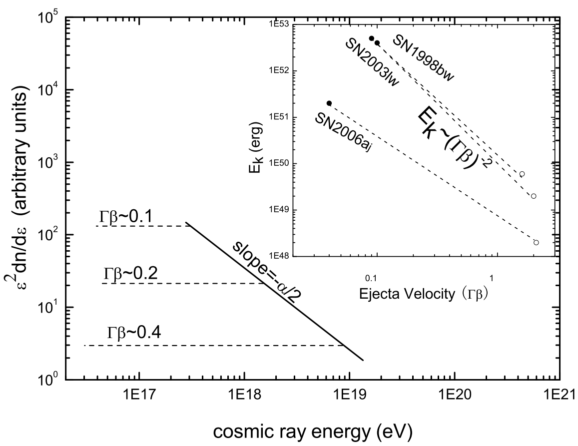

FIG. 1: The expected spectrum of CRs as a function of energy ε produced by hypernova remnants with a distribution of the ejecta kinetic energy with velocity $E_k \propto (\Gamma\beta)^{-\alpha}$. Dashed lines indicate the flat, injection spectrum ($\varepsilon^2 dn/d\varepsilon \propto \varepsilon^0$) from single velocity ejecta for three different velocities. The convolved contribution from different velocity ejecta, denoted by the solid line, leads to a spectrum $\varepsilon^2 dn/d\varepsilon \propto \varepsilon^{-\alpha/2}$. The inset shows the kinetic energy distribution of three nearby hypernovae associated with sub-energetic GRBs. The data points are from Ref.[27]. The solid and blank circles denote the energy of the slowest ejecta and the mildly relativistic ejecta, respectively. A kinetic energy distribution $E_k \propto (\Gamma\beta)^{-\alpha}$ (the solid line) gives a rough fit to the data of SN1998bw/GRB9802425 and SN2003lw/GRB031203 with $\alpha \sim 2.4$, while for SN2006aj/GRB060218, the slope is $\alpha \sim -1.7$.

In Figure 1 (inset) we show the kinetic energy distribution of the supernova ejecta associated with these three nearby sub-energetic GRBs, ranging from the bulk of the ejecta at $\Gamma\beta \simeq 0.1$ to the mildly relativistic ejecta ($\Gamma\beta \simeq 1$), where $\beta = v/c$ and Γ are the ejecta normalized velocity and bulk Lorentz factor, respectively. Surprisingly, even though the energy estimates of the high velocity ejecta from the radio observations are crude, all three hypernovae give a roughly consistent extrapolation of the slope of the kinetic energy distribution from the low to the high velocity end. SN1998bw and SN2003lw give a consistent slope of about ~ -2.4, while SN2006aj gives a slightly shallower distribution with a slope of ~ -1.7. Note that if the explosion is aspherical, the kinetic energy released in SN1998bw may be lower, $\sim 2 \times 10^{52}$erg [47], which will lead to a slightly shallower slope. It has been shown in [27] that the relatively shallow decay of the radio afterglow of GRB060218/SN2006aj can be modelled with a shock expansion $r \propto t^{0.85}$, appropriate for a core-collapse supernova explosion with a continuous distribution of ejecta velocities [28], propagating into a stellar wind environment of density $\rho \propto r^{-2}$. This provides a plausible scenario for a continuous distribution of the ejecta kinetic energy over velocities, ranging from the low velocity (0.1c) supernova bulk ejecta to the mildly relativistic ejecta within the same explosion, of the form

$$E_k \propto (\Gamma\beta)^{-\alpha}. \tag{1}$$

Such a distribution of velocities is naturally expected in an outflow spreading over a wide range of angles [29].

Standard hydrodynamic collapse calculations involving non-relativistic shocks result in a kinetic energy profile $E_k \propto (\Gamma\beta)^{-5}$ [21], with a negligible fraction of the kinetic energy at mildly relativistic velocities, consistent with the radio observations of, e.g., local type Ib/c supernovae 1994I and 2002ap. This very steep velocity profile implies negligible contribution to the highest energy CRs by high velocity ejecta [22]. On the other hand, ultra-relativistic shocks result in a much flatter profile, $E_k \propto (\Gamma\beta)^{-\alpha}$ with $\alpha \simeq 1$ [21]. For shocks in the trans-relativistic velocity regime, the energy distribution has not been calculated, but the above assumed slope of $\alpha \sim 2$ seems to be intermediate between the two extreme regimes. An important implication of such a continuous energy distribution in the semi-relativistic regime is that there is a significant amount of energy in the high-velocity ejecta of a hypernova. At this high velocity, the hypernova blast wave could accelerate CRs to energies as high as 10^{19} eV, as we show below.

Maximum energy of accelerated CRs. — Diffusive shock acceleration in supernova shock fronts has been extensively studied. The maximum energy for CR acceleration by the SNRs is usually thought to be limited to $\sim 10^{14} - 10^{15}$ eV for the case of typical interstellar magnetic fields of a few μG. It was suggested in Refs.[3] that the stellar wind from Wolf-Rayet (WR) star may have a relatively high magnetic field with a dominant component transverse to the shock normal, so that the SN explosion in these winds can accelerate particles to a much larger maximum energy. Recently there are also suggestions (e.g. [30]) that the magnetic field can be amplified non-linearly through MHD turbulence excited by the CRs in the vicinity of the shock to many times the pre-shock values, thus significantly increasing the acceleration rate and hence increasing the maximum energy. Amplification of the magnetic field to an equipartition value is generally assumed in radio SNRs and in GRB afterglow shocks, and has gained support from recent X-ray observations of several young SNRs[31]. We here consider a semi-relativistic hypernova ejecta with a velocity distribution given by Eq.(1), expanding in the stellar wind characteristic of WR stars, which are thought to be the progenitors of the hypernovae associated with GRBs. Different from Refs.[3], we here consider a random, CR-amplified magnetic field with a strength close to the equipartition value. During the free expansion phase, the magnetic field is $B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2$, where $\epsilon_B = 0.1\epsilon_{B,-1}$ is the fraction of the equipartition value of the magnetic field energy and ρ_w is the mass density of the stellar wind at radius R. The magnetic

field at the free-expansion radius R is

$$B = 0.03\epsilon_{B,-1}^{1/2} R_{18}^{-1} \left(\frac{v}{10^{10}\mathrm{cms}^{-1}}\right) \left(\frac{\dot{M}}{3\times10^{-5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}}\right)^{1/2} \times v_{w,3}^{-1/2}\mathrm{G}, \quad (2)$$

where $\dot{M}$ is the wind mass loss rate, whose average value is $3\times10^{-5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}$ for WR stars, and $v_w = 10^3 v_{w,3}$ km/s is the wind velocity. The maximum energy that can be attained in a shock depends on the magnetic field configuration. If the magnetic field is mostly perpendicular to the shock surface, the scattering coefficient for particles is smaller than in the case of a parallel shock and as a result, the maximum energy is given by $\simeq ZeBR$ [32]. In our case, however, we assume that the CR-amplified magnetic field is random in direction and the maximum energy of the accelerated particles is (e.g. [30, 33])

$$\varepsilon_{\max} \simeq ZeBR\beta = 4\times10^{18}Z \times\epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}\mathrm{cms}^{-1}}\right)^2 \left(\frac{\dot{M}}{3\times10^{-5}\mathrm{M}_{\odot}\mathrm{yr}^{-1}}\right)^{1/2} v_{w,3}^{-1/2}\mathrm{eV}. \quad (3)$$

The stellar wind of WR stars is composed largely of H and He ($Z = 1$ and $Z = 2$, respectively). In this shock acceleration scenario, the maximum energy $\varepsilon_{\max}$ is proportional to the square of the shock velocity, so a higher velocity hypernova ejecta can lead to a higher $\varepsilon_{\max}$. Note also that during the free expansion phase of the ejecta, $\varepsilon_{\max}$ is independent of the radius. For the assumed velocity distribution of Eq.(1), the bulk of the ejecta has a velocity of $0.1c$ and the maximum CR energy corresponding to this (low-end) velocity ejecta is about $10^{17.5}Z$ eV for typical parameters of the stellar wind.

The spectrum of the CRs. — For a single velocity ejecta, the differential spectrum of the accelerated protons is given by the injection spectrum, which is $dN/d\varepsilon \propto \varepsilon^{-\gamma}$ with $\gamma \simeq 2.0$, for both non-relativistic shocks and semi-relativistic shocks [34]. However, if the hypernova produces a kinetic energy distribution spread over the velocity with the same explosion, as described by Eq.(1), the final CR spectrum detected at Earth is determined by the kinetic energy distribution profile, as illustrated in Fig.1. This can be understood as higher energy CRs being contributed dominantly by higher velocity ejecta, which are represented with a smaller total energy. As the maximum CR energy for a particular velocity is $\varepsilon_{\max} \propto (\Gamma\beta)^2$ and the energy distribution of the ejecta is $E_k \propto (\Gamma\beta)^{-\alpha}$, we see that $E_k \propto \varepsilon_{\max}^{-\alpha/2}$. Convolving the contribution from the different velocity ejecta (Fig.1), we expect a final differential energy spectrum of the CRs of the form

$$\varepsilon^2(dN/d\varepsilon) \propto \varepsilon^{-\alpha/2}, \quad (4)$$

where ε is the energy of cosmic ray particles, which relates to the ejecta kinetic energy as $E_k(\varepsilon) \propto \varepsilon^2(dN/d\varepsilon)$. Fits to the observed CR data give a differential spectrum $J = C(E/6.3\times10^{18}\mathrm{eV})^{-3.20\pm0.05}$ for $4\times10^{17}\mathrm{eV} < E < 6.3\times10^{18}\mathrm{eV}$ and $J = C(E/6.3\times10^{18}\mathrm{eV})^{-2.75\pm0.2}$ for $6.3\times10^{18}\mathrm{eV} < E < 4\times10^{19}\mathrm{eV}$ with $C = (9.23\pm0.65)\times10^{-33}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{eV}^{-1}$ [5]. The observed spectral slope at energies $4\times10^{17}\mathrm{eV} < E < 6.3\times10^{18}\mathrm{eV}$ implies $\alpha = 2.40\pm0.1$ in Eq. (4), which is roughly consistent with the theoretical slope deduced in Fig.1. Note that the energy losses due to photo-pair production with CMB may become important above $\sim 10^{18}$ eV and thus steepening the injection spectrum [9]. However, the details depend on the specific value of the injection spectrum and source evolution. In all cases this is a small correction which can be accommodated by using a slightly smaller value for α and thus a slightly harder injection spectrum from the HNe.

Hypernova rates and the observed flux — We estimate now how many SN1998bw-like hypernovae per unit volume per unit time are needed to produce the CR flux from 6×10^{17} to 10^{19} eV. Assuming that the kinetic energy output from one SN1998bw-like hypernova is $E_{k,\mathrm{HN}} = 5\times10^{52}$ erg , the local kinetic energy release rate by hypernovae is

$$\dot{\epsilon_k}(z=0) = R_{\mathrm{HN}}E_{k,\mathrm{HN}} = 2.5\times10^{46}\left(\frac{R_{\mathrm{HN}}}{500\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right)\mathrm{erg\ Mpc}^{-3}\ \mathrm{yr}^{-1} \quad (5)$$

Adopting an efficiency factor 1/6 for the conversion of ejecta kinetic energy into CR energy [6], and $1/\ln(\varepsilon_{max}/\varepsilon_{min}) \simeq 0.1$ as the fraction of the total CR energy that is contributed by each decade of energy, the local CR energy generation rate per energy decade at $10^{17.5}Z$ eV, corresponding to $v = 0.1c$, is $\dot{\epsilon}_{CR,0} = 0.016\dot{\epsilon_k}(z=0)$. The corresponding expected CR flux is

$$\varepsilon^2 J = (c/4\pi H_0)\dot{\epsilon}_{CR,0}f_z \quad (6)$$

where $H_0 = 70$ km s^{-1} Mpc^{-1} is the Hubble constant and

$$f_z = H_0\int_0^{z_{\max}} dz(dt/dz)S(z)(1+z)^{-1} \quad (7)$$

is the correction factor for the contribution from high-redshift sources. Here $(dt/dz) = H^{-1}(z)/(1+z)$, with $H(z)$ being the Hubble parameter at cosmological epoch z, and $z_{\max}$ is the maximum redshift corresponding to the mean free path against photopion production in the CMB, whose value is $z_{\max} \gtrsim 4$ for protons with energies $\lesssim 10^{19}$eV. The value of f_z is $\sim 2-3$ for $z_{\max} = 4$ and for the source evolution function $S(z)$ given by different star formation rates (SFR) in Ref. [38] or the broken power-law estimate in Ref. [39] for a standard ΛCDM cosmology. Here we assume $f_z \approx 3$. At $\varepsilon = 10^{17.5}Z$ eV, we get a CR flux of

$$J = 10^{-28}Z^{-2}\left(\frac{R_{\mathrm{HN}}}{500\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}}\right)\left(\frac{f_z}{3}\right)\mathrm{eV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1} \quad (8)$$

Comparing this to the observed CR flux of $1.5\times10^{-28}(\varepsilon/10^{17.5}\ \mathrm{eV})^{-3.2}$, we infer a required hypernova rate of

$$R_{\mathrm{HN}} = 750Z^{-1.2}(f_z/3)^{-1}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \quad (9)$$

Assuming Z=1 (or 2) and $f_z = 3$, one can derive a required hypernova rate of $330 - 750$ $\mathrm{Gpc^{-3}yr^{-1}}$. Comparing this with the local rate of "normal" type Ib/c SNe, $\sim 2-5\times10^4$ $\mathrm{Gpc^{-3}yr^{-1}}$ [36, 37], one can find that the ratio of the required hypernovae rate to the normal Ib/c SNe rate is $\sim 1-4\%$, which is consistent with the value observed in the local universe $\sim 7\%$ [36]. The required semi-relativistic hypernova rate is also consistent with the observed rate of low-luminosity GRBs [27, 35, 36]. Since different SFR give different values of f_z, one can in principle use the required hypernova rate to constrain f_z and therefore constrain the SFR.

Neutrino emission from CRs interacting with hypernova photons.— The kinetic energy of the highest velocity ejecta of hypernovae is converted into the highest energy CRs in a relatively short time, given by the free expansion time $t < t_{\rm dec}$ before the ejecta is decelerated by the swept-up stellar wind. During this time the hypernovae remain very bright in the optical-UV band. As a consequence, the high-energy protons can interact with the hypernova optical-UV photons during the first tens of days after the explosion, leading to $p\gamma$ neutrino production. This neutrino production mechanism differs in its origins from another, recently suggested neutrino production scheme in low-luminosity GRBs [40], which involves the usual internal shock model for the acceleration of protons and production of the target photons. It also differs from the suggested mechanism of neutrino production in starburst galaxies, where neutrinos are thought to arise from $pp(pn)$ interactions between the accelerated protons and the interstellar medium [41].

Around the peak photon luminosity time (typically a few tens of days) of type Ib/c supernovae, only the high velocity ejecta with $\Gamma\beta \gtrsim 1$ has been decelerated, and only about 2×10^{50} erg of energy goes into such high velocity ejecta. The resulting high-energy protons are above the photopion interaction threshold with thermal hypernova photons if their energy satisfies $\varepsilon_p\varepsilon_\gamma \gtrsim 0.3\mathrm{GeV}^2$, i.e. $\varepsilon_p \gtrsim 10^{18}$eV for UV-optical photons. The cooling rate of a proton of energy ε_p due to pion production via Δ^+ resonance is $t_{p\gamma}^{-1} \equiv E^{-1}(dE/dt) \simeq n(\varepsilon_\gamma)\sigma_{peak}c\xi_{\rm peak}(\Delta\varepsilon/\varepsilon_{peak})$. Here $n(\varepsilon_\gamma)$ is the number density of hypernova photons at the peak of the black-body distribution, $\sigma_{peak} = 5\times10^{-28}$ $\mathrm{cm^{-2}}$ is the cross section for pion production for a photon with energy $\epsilon = \varepsilon_{peak} = 0.3$ GeV in the proton rest frame, $\xi_{peak} = 0.2$ is the average fraction of energy lost to the pion, and $\Delta\varepsilon = 0.2$GeV is the peak width. Thus, the fraction of energy lost by protons to pions is

$$\begin{aligned} f_{p\gamma} &= R/(\Gamma\beta c t_{p\gamma}) \\ &= 0.2 L_{\rm SN,43}(R/10^{16}\ \mathrm{cm})^{-1}(\varepsilon_\gamma/1\ \mathrm{eV})^{-1} \end{aligned} \tag{10}$$

where $L_{\rm SN} \simeq 10^{43}$ erg $\mathrm{s^{-1}}$ is the bolometric luminosity of SN1998bw around its peak brightness (see e.g. [15]) and $\varepsilon_\gamma = 1$ eV is taken as the optical photon energy. The ν_μ ($\bar\nu_\mu$) from pion decays will have a typical energy $0.05\varepsilon_p$ and the expected diffuse neutrino flux is

$$\begin{aligned} &\varepsilon_\nu^2\Phi_{\nu_\mu} \simeq \tfrac{1}{8} f_{p\gamma}(\varepsilon_p^2 J_p)_{(\Gamma\beta\geq1)} = 0.3\times10^{-10} \\ &\times\left(\tfrac{R_{HE}}{500\mathrm{Gpc^{-3}yr^{-1}}}\right)\left(\tfrac{f_{p\gamma}}{0.2}\right)\left(\tfrac{f_z}{3}\right)\ \mathrm{GeV\ cm^{-2}s^{-1}sr^{-1}} \end{aligned} \tag{11}$$

For the thermal spectrum of the target photons, only a small energy range of protons with $\varepsilon_p > 10^{18}$eV can interact effectively with the photons, so we expect the neutrino diffuse emission to peak at $\sim 5\times10^{16}$ eV. The maximum neutrino energy would be 1.5×10^{18} eV corresponding to the maximum CR energy of 3×10^{19} eV. The probability for a high-energy muon neutrino to interact in ice/water producing a high-energy muon detected by the embedded instruments is $P(\varepsilon_\nu) \approx 4.6\times10^{-4}(\varepsilon_\nu/\mathrm{PeV})^{0.55}$ in the PeV-EeV range [42]. Integrating the flux in Eq.(11) times the probability in the $5\times10^{17}-1.5\times10^{18}$ eV range, we get an event rate of $\approx 10^{-2}$ $\mathrm{yr^{-1}\ km^{-2}}$ over 2π sr in a neutrino telescope. Including muon anti-neutrinos would increase the rate by a factor 2. This rate is too low for cubic kilometer detectors, but future $\gtrsim 100$ $\mathrm{km^2}$ telescopes such as ANITA and ARIANNA may detect these ultra-high energy neutrinos [43].

Discussion.— We have proposed that cosmic rays from the second knee to 10^{19} eV, whose origin has been debated, may be produced by extra-galactic hypernovae similar to SN1998bw, which are associated with under-energetic GRBs. The CRs below the second knee may be due to heavy ions accelerated in Galactic sources, such as Galactic supernovae expanding into the ISM [6] or stellar winds [3], and Galactic trans-relativistic hypernovae [44]. This is supported by the measurements from KASCADE [4] that above the "knee" at 3×10^{15} eV the chemical composition is increasingly richer in heavy nuclei. Recent HiRes measurements [13] found that the chemical composition changes back towards lighter (proton) composition at and above the "second knee", suggesting a transition from Galactic CRs to extra-galactic CRs that consist primarily of protons. A smooth transition in the CR spectrum between Galactic and extra-galactic components may be reasonable, according to the numerical estimates by Hillas (see Fig.8 of [45]), who found that the rapidly falling spectrum may accommodate a factor of 3 or more uncertainty in the extra-galactic component without providing a visible clue to the joint point of the overall spectrum. Berezinsky et al.[9] also considered an extra-galactic origin of the cosmic-rays above the second knee, similar to us, but with a single component extending up to the highest energy that originates from AGNs. The so-called "dip" between the second knee and the ankle, i.e. first steepening and then hardening of the spectrum, has been suggested as being due to adiabatic and pair-production energy losses by cosmic-ray protons. In a multi-component model such as ours, the "dip" can arise due to a steep injection spectrum, from HNe above the second knee (modulo small adiabatic and pair-production energy losses) which is taken over by a harder spectrum from normal GRBs above the ankle. Since hypernovae/under-energetic GRBs belong to the

same class as normal GRBs, one should also expect a natural flux matching at the ankle from these two components.

We have shown that semi-relativistic hypernovae can accelerate CRs to energies $\lesssim 10^{19}$ eV, and provide the right flux density between the second knee at 6×10^{17} eV and 10^{19} eV. The assumed ejecta velocity distribution profile is consistent with current supernova-GRB observations. Confirmation of its theoretical plausibility would require further detailed numerical investigations of hypernova explosions and shock propagation through the progenitor envelope.

Recently, there has been evidence indicating that both normal GRBs and sub-energetic GRBs associated with hypernovae are preferentially found in low-metallicity galaxies [46]. This would imply that hypernova rates in normal metallicity galaxies such as our Milky Way may be low, so that the Galactic contribution to the highest energy CRs would be unimportant [48]. Most of the flux would thus be expected to originate in distant, low-metallicity galaxies and the distribution of these cosmic rays should be isotropic. Since the propagation of the cosmic rays in the energy range $6 \times 10^{17} - 10^{19}$ eV may be significantly deflected by the magnetic field in our Galaxy, and possibly by the intergalactic magnetic field as well, there would be no expected correlation between the arrival direction of cosmic rays in this energy range and the hypernova host galaxies.

We would like to thank E. Waxman, C. D. Dermer, T. K. Gaisser and P. Sommers for fruitful discussions. This work is supported in part by NASA NAG5-13286, NSF AST 0307376, and the National Natural Science Foundation of China under grants 10403002 and 10221001, and the Foundation for the Authors of National Excellent Doctoral Dissertations of China (for X.Y.W.).

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[48] A low metallicity host galaxy requirement for hypernovae is not yet firmly established; without this requirement, galactic hypernovae might also be potential high energy CR sources [44], if the galactic rate and the CR containment time are sufficiently large.